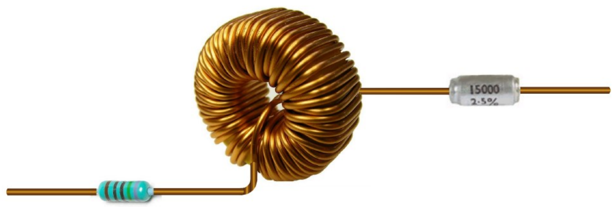
Brass Tacks

An in-depth look at a radio-related topic

Inductors and capacitors



The three most fundamental passive electronic components are resistors, inductors, and capacitors. This basic discussion focuses on the ***inductor*** and ***capacitor***, and explains the functions and purposes of these important devices and how they're used in circuits. The hope is to give you a high-level understanding of it without drowning you in excessive detail.

One property shared by resistors, inductors, and capacitors is their ability to oppose current flow in a circuit. This flow opposition is not a decrease in *current speed*, but a ***decrease in current volume***, meaning number of charges being allowed to pass through it per second. A resistor opposes the flow of electrical current proportional to the voltage across it. With resistors, the opposition to current flow occurs because of ***resistance***, but with inductors and capacitors, the opposition to current flow occurs due to ***reactance***, which depends on the frequency of the current. In short,

- an inductor ***increases*** its opposition to current flow as the current's ***frequency increases***
- a capacitor ***decreases*** its opposition to current flow as the current's ***frequency increases***
- a resistor ***maintains*** its opposition to current flow, ***regardless of frequency***.

An interesting discussion also follows about what effect they have on circuits where they're used in multiples with each other or in combination with the other components. For now, let's explore the inductor and capacitor, saving the discussion of the resistor for another article.

Inductors

Inductor symbol

An inductor is a component that stores energy in a magnetic field, and is commonly made from a coil of wire wrapped around metal or air. Technically, it's any device whose property of *inductance* is the ratio of the voltage across it to the rate of change of the current through it. Common inductors include chokes, transformers, coils, solenoids, and simply wires. This means any two wires, or even a single wire bent on itself, forms an inductor.

As mentioned, an inductor opposes the flow of current like a resistor does, but its opposition to current flow is frequency-dependent; that is, the opposition increases as the frequency of the current through it increases. This current flow opposition is known as *inductive reactance*, and is defined as

$$X_L = 2\pi f L$$ (measured in *ohms*, symbol Ω)

in which **f** is the frequency in Hertz (Hz) and **L** is the inductance of the inductor in Henries (H). As you can see, X_L approaches zero as the frequency gets closer to zero, meaning an inductor at 0 Hz acts like a zero-resistance wire, or short circuit. By the same token, X_L becomes larger as the frequency increases. Therefore, its *opposition to current flow increases with frequency*.

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Like for resistors, the total value of inductors placed in series with each other is the sum of their inductances, while the total value of two inductors placed in parallel with each other is their product over their sum.

$$L_T = L_1 + L_2 \qquad\qquad L_T = \frac{L_1 \times L_2}{L_1 + L_2}$$

Series inductances ***Parallel inductances***

The everyday inductor

You might recall that a magnetic needle compass works by pointing in the direction of Earth's magnetic field. If you send a current through a wire, it creates a magnetic field around the wire, and the influence of the magnetic field can be shown by bringing the wire next to the compass when you close the switch to complete the circuit with a battery, deflecting the compass needle. This is known as Oersted's Experiment.

If you coil the wire into a small loop, the strength of the magnetic field created by the same current in the wire will increase. In fact, the magnetic field strength will be multiplied by the number of turns in your coil. You can test this by wrapping one loop of wire around a nail, then connecting the wire across a battery. You'll discover that the more loops of wire you have around the nail, the more metal paper clips it can pick up.

Capacitors

Capacitor symbol

A capacitor is a component that stores energy in an electric field, and is commonly made from two plates, sheets of metal, or other flat conductors facing each other, separated by insulating material we call a *dielectric*. Technically, it's any device whose property of capacitance is the ratio of the current through it to the rate of change of the voltage across it.

As mentioned, a capacitor opposes the flow of current like a resistor does, but its opposition to current flow is frequency-dependent. This current flow opposition is known as *capacitive reactance*, and is defined as

$$\mathbf{X_C = 1/(2\pi fC)}$$ (measured in *ohms*, symbol Ω)

in which **f** is the frequency and **C** is the capacitance of the capacitor in Farads (F). As you can see, $\mathbf{X_c}$ becomes larger as the frequency decreases, meaning a capacitor approaching 0 Hz acts like an infinite-resistance wire, or open circuit; by the same token, $\mathbf{X_c}$ becomes smaller as the frequency is increased. Therefore, its *opposition to current flow decreases with frequency*.

Unlike for resistors and inductors, the total value of capacitors placed in parallel with each other is the sum of their capacitances, while the total value of two capacitors placed in series with each other is their product over their sum.

$$C_T = C_1 + C_2 \qquad\qquad C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

Parallel capacitances ***Series capacitances***

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The everyday capacitor

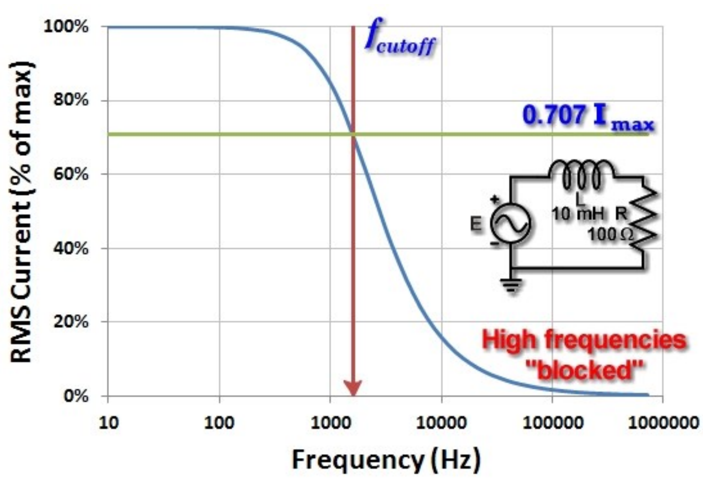
As you shuffle your feet while walking across the carpet on a dry day, the friction in your shoes will collect a lot of static charge. Before you touch anything to discharge that static, your body will hold that charge like an electric storage tank, making you into a living capacitor. For a more radio-related example, examine an ordinary dipole antenna, which is often little more than two wires with no direct electrical connection to each other. The energy radiated from one element of the dipole is returned to the other element by capacitance.

While capacitance is absolutely necessary for amateur radio antennas to work, there are times when capacitance is less-than-helpful. Any two electrically conductive objects can act as the two terminals of a capacitor, using whatever is in between them as a dielectric. This is true when you mount your antenna close to your metal shed, metal siding, stucco, the ground (dirt), or your kids' swing set. Due to the capacitive coupling your antenna will have with these objects, part of your hard-earned RF (radio frequency) signal will be absorbed by them.

Inductors and capacitors as filters

The frequency-related opposition to current flow as discussed is not truly *resistance* in the purest sense of the word, so we call it *attenuation*, or signal strength reduction. Because inductors and capacitors can attenuate electrical signals depending on the signal frequency, they can be used to filter out unwanted signals, such as static, noise, interference, and even legitimate signals that might be too close to your own working frequency.

An inductor exhibits greater attenuation with increasing frequency, as shown by the following *frequency response* graph, that of a *low-pass filter*, which allows signals of lower-frequency to pass through:



An electronic filter cannot completely filter out *all* signals past a specific frequency, as though it was a switch. So, it's agreed that *most* practical filtering will result in reducing the input by a

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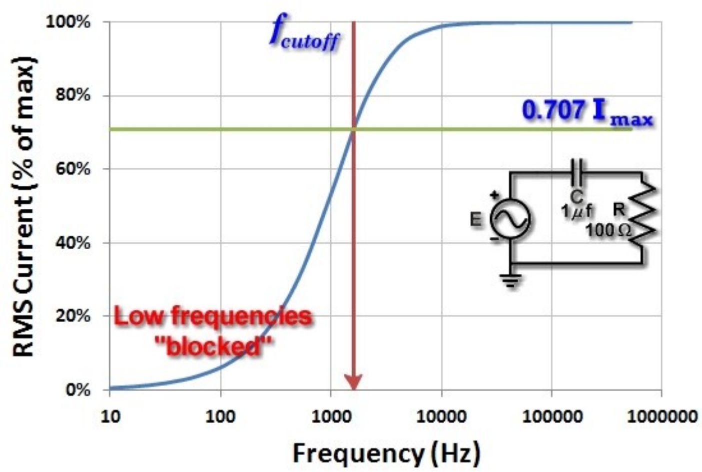
half, or –3 dB. Signals of frequencies higher than that point are considered sufficiently attenuated for most practical purposes. For an inductor, that frequency point is calculated as

$$f_c = \frac{R}{2\pi L}$$

in which **R** is the series resistance and **L** is the inductance. f_c is known as the *cutoff frequency* or *corner frequency* or *center frequency* (fortunately in English, all these words start with "c" which simplifies the notation), the point at which the output power is half the input power.

A capacitor exhibits lesser attenuation with increasing frequency, as shown by the following frequency response graph, that of a *high-pass filter*, which allows signals of higher-frequency to pass through:



This cutoff frequency arises from the time constant for either an inductor or capacitor. For a capacitor, the cutoff frequency is defined as

$$f_c = \frac{1}{2\pi RC}$$

in which **R** is the series resistance and **C** is the capacitance, f_c again being the resulting cutoff frequency. In this case, all signals of frequencies higher than this will be effectively attenuated.

Armed with these two filter types, one using an inductor, and the other using a capacitor, we can construct what's known as a *band-pass filter*, which allows only signals whose frequencies are higher than the low-pass filter and lower than the high-pass filter to pass through. The advantage of such a filter is the ability to focus on a signal of a particular frequency, or small frequency range (known as a *band*), and reject or attenuate all surrounding signals. It's kind of like walking into a noisy party, but only wanting to talk with one of the guests.

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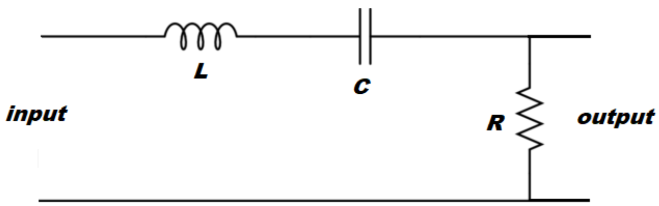
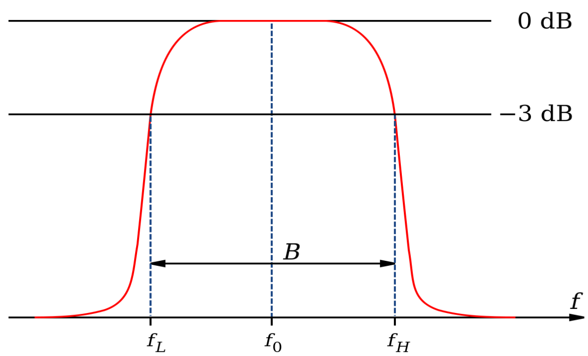
Let's say we wanted to construct a bandpass filter that attenuates all noise and other signals outside a particular band, such as a segment within the 40-meter band, say, from 7.074 MHz to 7.230 MHz, using the following simple (we often call it an RLC) circuit:



As you can see, if the input signal frequency is too high, the inductor will attenuate that signal, and if it's too low, the capacitor will, so we're on the right track. This circuit will help us achieve the following frequency response graph:



To accomplish this, set

$$f_L = \frac{R}{2\pi L} = 7.074\ MHz$$

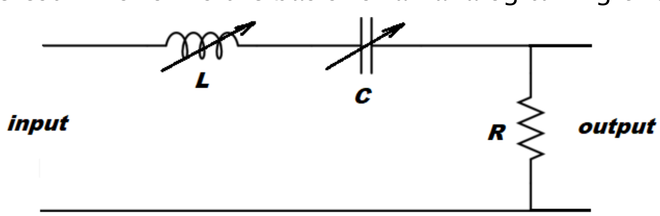
$$f_H = \frac{1}{2\pi RC} = 7.230\ MHz$$

Then, using a 150-ohm resistor (assuming a low-power receiver), solve for **L** and **C**:

L = 3.3 µH and **C = 150 pF**

Solder these three in place, and your bandpass filter is complete, as long as you have a way to connect the input and output wires to it. Because a "band" of frequencies is allowed to pass through this circuit, the band has a frequency "width," and we call that its *bandwidth*, calculated simply as ***B*** **=** $f_H - f_L$, in our case, ***B = 7.230 MHz – 7.074 MHz = 0.156 MHz = 156 kHz.***

If we replace the fixed inductor with a variable inductor, or the fixed capacitor with a variable capacitor (or both), we can use this type of filter as a crude tuning circuit, to selectively admit the frequencies of interest. This forms the basis for an analog tuning circuit:



This allows you to create the bandpass filter as you did above, but allow for some wiggle room, in case you need a little extra bandwidth, or need to filter out a little bit more noise.

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Inductors and capacitors in resonance

It turns out that an inductor in parallel or series with a capacitor creates what's known as a *resonant* circuit, a passive device that also acts as a sort of very narrow-bandwidth bandpass filter. The definition of resonance is the cancellation of the inductive reactance and capacitive reactance in an impedance. The theory behind a resonant circuit is that its minimum impedance occurs at a particular frequency; indeed, the impedance is assumed to be 0 ohms (short circuit) at the frequency of interest, and high impedance (open circuit) at other frequencies.

For convenience (and simplicity), let's design a *trap* for a 40-meter dipole, so that it's also resonant on 20 meters. To achieve that, let's assume the trap inhibits all signals except those for 40 meters, (This is convenient, because it'll allow us to modify it further later for, say, 15 meters, if we wanted to.) This means the trap acts like a wire (0-ohm short circuit) at 40 meters, say, 7.2 MHz. Performing the math for impedance, then, yields

$$Z = R + jX = 0 \text{ ohms}$$

Since the wire is short enough (65 feet) to assume that its resistance **R** is also 0 ohms,

$$0 = 0 + j0 \text{ ohms}; \text{ therefore, } X = 0, \text{ but}$$

$$X = X_L - X_C = 2\pi fL - 1/(2\pi fC) = 0$$

$$2\pi fL = 1/(2\pi fC)$$

Then, solving for C, we have

$$C = 1/(4\pi^2 f^2 L)$$

If we create an inductor out of a length of coiled wire, and measured it on an analyzer, let's say it displays around 40.7 μH of inductance. The capacitor value is therefore

$$C = 1/[4\pi^2(7.2\text{ MHz})^2(40.7\ \mu\text{H})] = 12\text{ pF}$$

Therefore, place a 12 pF capacitor in series with your 40.7 μH coil, and you've got yourself a 20-meter / 40-meter trap antenna. It'll be the correct length for a 20-meter dipole antenna, and then seem a lot longer to your transceiver when you attempt to transmit on 40 meters.

Finally

Another use for inductors and capacitors is coupling two or more circuits together. An isolation transformer, for example, uses inductive coupling to connect two circuits that are separated due to large voltage differences. A glass-mount antenna uses capacitive coupling to complete its transmission line connection through the vehicle window. Similar technology is employed where your conductive skin capacitively couples with the internal circuitry of your smartphone as you touch the non-conductive keypad or other areas of the display.

Noji Ratzlaff, KNØJI (kn0ji@arrl.net)